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Scaling of increased dissolved organic carbon inputs by forest clear-cutting – What arrives downstream?

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SUMMARY

Forest clear-cutting has been found to significantly increase concentrations of dissolved organic carbon (DOC) in boreal first-order streams. Here, we address the questions of (1) how the additional inputs of DOC by upstream forest harvesting affect downstream locations within a stream network and (2) what catchment area has to be harvested to cause a significant downstream increase in DOC concentration. We combined the use of primary data from a paired-catchment experiment, clear-cut history of a nested stream network derived from satellite images with a mixing-model approach in order to quantify the importance of upstream clear-cuts on two downstream sites with different catchment sizes. Modeled [DOC] agreed well with the measured concentrations in the smaller, 8.7 km^2 catchment located above a larger wetland area, but discrepancies occurred for the larger 22.9 km^2 catchment located downstream of the wetland. Estimates of the critical area ($A_{critical}$) needed to be harvested to cause a significant impact on downstream DOC concentrations was quantified to be 11% for $p < 0.05$ and 23–25% for $p < 0.001$. Our results suggests that (i) increased DOC concentrations induced by forest harvesting affect downstream sites and (ii) additional DOC inputs by harvests have a significant impact on stream water quality, if harvests exceed $A_{critical}$. We suggest that the estimates of $A_{critical}$ could be used in sensitive river networks to provide harvesting-thresholds. The latter could be implemented into forest planning that includes considerations of the negative impact of clear-cutting on water quality.

1. Introduction

Dissolved organic carbon (DOC) in stream water is a fundamental biogeochemical constituent shaping stream ecosystems. DOC alters the acid-state by its large proportion of humic acids (Hruska et al., 2003; McLaughlin et al., 1996), affects light use efficiency (Karlsson et al., 2009), acts as a transport vector for lateral carbon fluxes leaving the ecosystems (Battin et al., 2008; Wallin et al., 2013) and is often the most important ligand for toxins and metals such as mercury (Burns et al., 2013), arsenic (Huser et al., 2011) and persistent organic pollutants (Bergknut et al., 2010).

Streams have been shown to be considerably affected by catchment perturbations such as forestry operations. Clear-cutting results in an increased mobilization of various nutrients, such as nitrogen (N), phosphorous and carbon (C) into streams (Bormann et al., 1968; Kreutzweiser et al., 2008). However, in N-limited boreal regions where catchment soils store large amounts of carbon (Jobbágy and Jackson, 2000), the leaching of N into surface waters is less pronounced (Futter et al., 2010), whereas the mobilization of organic carbon into stream water is of high importance (Bolan et al., 2011). Boreal first-order streams, which represent the smallest continuously flowing watercourses in the landscape, have hence been shown to significantly increase in DOC concentrations as a response to clear-cutting (Kreutzweiser et al., 2008; Laudon et al., 2009; Nieminen, 2004; Schelker et al., 2012). Furthermore these increases are paralleled by the increased runoff caused by the reduction of evapotranspiration during summer following the deforestation (Andréassian, 2004; Hornbeck et al., 1993; Schelker et al., 2013).

However, when first-order streams merge and form a larger-scale stream network, DOC from various landscape source areas is mixed and processed to define the downstream DOC signal observed at the outlet (Laudon et al., 2011). In undisturbed boreal stream networks DOC is regulated by riparian wetlands that often have peat rich soils, low elevation mires that may or may not be forested, and open water bodies (Bishop et al., 2004). Furthermore, the DOC signal at the outlet may also depend on in-stream processes. For example, removal of labile fractions of DOC can take place within the stream network, either as direct uptake of DOC by stream biota with a subsequent loss

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of CO_2 through respiration (Berggren et al., 2007) or by hyporheic processing (Zarnetske et al., 2011). Furthermore, DOC processing within connected water bodies such as lakes and ponds in the stream network may lead to additional losses of DOC via respiration and sedimentation (Ask et al., 2012; Cole et al., 2002). In contrast, DOC production due to photosynthesis that is often found in eutrophic water bodies (Henderson et al., 2008) is considered to play a minimal role in nutrient-poor boreal lakes (Karlsson et al., 2009).

Assessing the impact of forestry on water quality at larger landscape scales is not trivial. Partly this is due to the complexity of quantifying the cumulative effects on water quality resulting from multiple harvesting activities occurring at different times within a watershed. Furthermore, the combined effects of increased concentration and runoff will increase the relative contribution of disturbed catchments to the downstream chemical signal (Alexander et al., 2007). Whereas paired-catchment studies provide a useful tool to quantify the effects of forest clear-cutting in small, first-order catchments (see Bormann et al., 1968 for a classical example), linking "cause-and-effect" (Mallik and Teichert, 2009) of local perturbations in larger scale catchments remain a major challenge. One suggested solution of this problem is the use of modeling approaches (Buttle et al., 2005), such as for example simple mixing models (Öhman et al., 2009) or more complex, distributed hydrological models (Alila and Beckers, 2001).

Nevertheless, the question of what role increased DOC inputs from forest clear-cutting play for the stream network located downstream and how clear-cutting affects DOC concentrations in larger rivers remain subject of great interest (Buttle et al., 2009; Futter et al., 2011). Whereas some importance in this topic arises from a process-understanding perspective, there is also a practical component to this question: If forest management aims at maintaining good water quality, which is an important ecosystem service (Futter et al., 2011), how does forest management need to be adjusted to follow this requirement (Eriksson et al., 2011)?

In this study we therefore specifically address the question of how important forest clear-cutting is for the DOC concentrations in downstream locations. We hypothesize (i) that clear-cutting impacted first-order streams alter downstream water quality and (ii) that downstream DOC concentrations of a larger stream can be significantly higher than those of an undisturbed stream of the same size, if the relative percentage of clear-cutting area within a larger catchment exceeds threshold values.

2. Methods

2.1. Study site

This study was conducted to the Balsjö paired catchment experiment in northern Sweden (Fig. 1). The vegetation in the Balsjö watershed is typical for the boreal region of Scandinavia which is characterized by three different landscape features consisting of upland forests, wetlands and open water bodies. Uplands are commonly characterized by gentle slopes originating from the last glaciation, with shallow, well drained till soils (orthic podsols) that are underlain by bedrock (pegmatite, aplitic granite and aplite). Flat valley bottoms are dominated by wetlands. Wetland soils are classified as histosols with peat layers that can be several meters thick. In Balsjö, Scots pine (*Pinus sylvestris*) dominates the upland locations. Norway spruce (*Picea abies*) is the most abundant tree species in the middle and lower parts of the catchment (Löfgren et al., 2009b). Near stream zones and wetlands are dominated by birch (*Betula* spp.) and various moss species (Schelker et al., 2013). On hillslopes, dwarf shrubs such as *Vaccinium* species or cowberry (*Empetrum* sp.) dominate the understory vegetation, whereas the ground vegetation consists of forbs, grasses and sedges.

Earlier studies performed at the Balsjö catchment have primarily focused on quantifying the hydrological and biogeochemical changes, respectively, following clear-cutting in small first-order streams (Löfgren et al., 2009b; Schelker et al., 2012; Sørensen et al., 2009) that range in catchment area between 24 and 156 ha. In contrast, this study also includes two larger downstream locations named BA-1 and BA-2 located along the river 'Balån' (Fig. 1), earlier used for assessing ecological status according to the EU water framework directive (Löfgren et al., 2009a). Whereas BA-1 marks the main outlet of the stream network with a

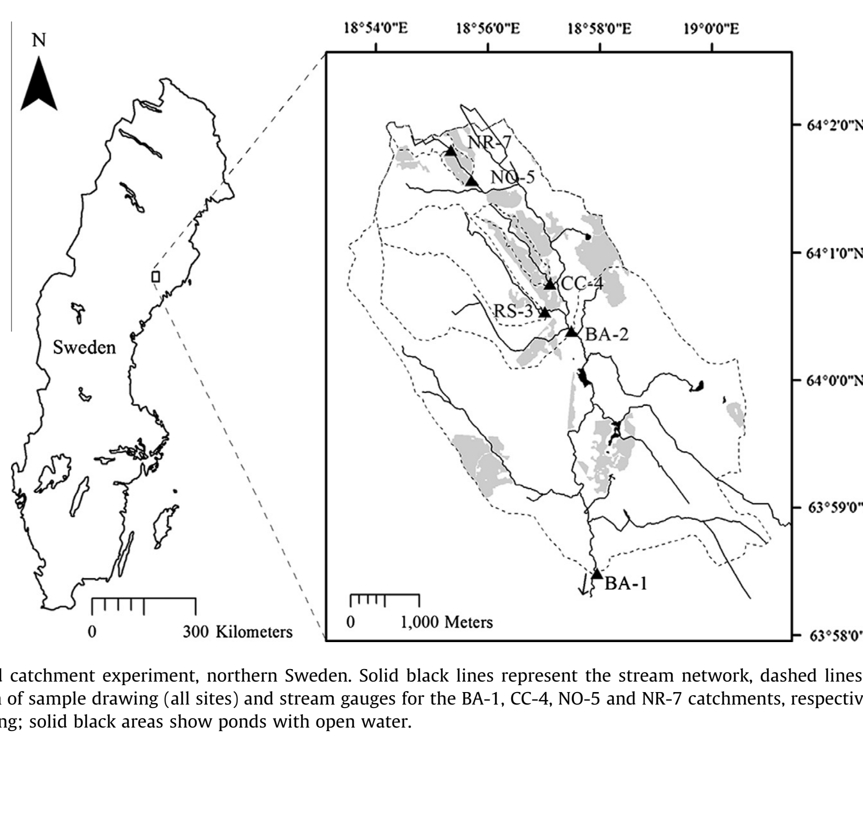

Fig. 1. The '277 Balsjö' paired catchment experiment, northern Sweden. Solid black lines represent the stream network, dashed lines the catchment boundaries; black pyramids indicate the location of sample drawing (all sites) and stream gauges for the BA-1, CC-4, NO-5 and NR-7 catchments, respectively. Areas harvested during 2000–2011 are shown as grey shading; solid black areas show ponds with open water.